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THE EFFECT OF VARIOUS STRAINING MANEUVERS ON CARDIAC VOLUMES AT 1G AND DURING +Gz ACCELERATION

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FOR THE COMMANDER

James W. Brinkley

JAMES W. BRINKLEY
Director
Biodynamics and Bioengineering Division
Harry G. Armstrong Aerospace Medical Research Laboratory

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The purpose of this study was to evaluate the effect of Valsalva (Val), isometric contraction (Iso) and the L-1 maneuvers (L-1) on cardiac volumes at 1G and during 4G. Two-dimensional echocardiography was used to measure volumes. 1G Phase: Eight seated male subjects performed the three maneuvers. The end-diastolic volume (EDV) decreased during Val and L-1 ($p < 0.05$). EDV decreased initially but then returned to baseline with Iso. 4G Phase: Seven male subjects experienced three 30 second 4G epochs while performing the three maneuvers. During 4G, 3 of 7 performing Val, 2 of 7 performing Iso, and none performing L-1, experienced peripheral light loss. EDV decreased and stabilized below baseline during the 4Gz epoch ($p < 0.05$). Heart rate and cardiac output increased for all maneuvers. Differences between the effects of Val, Iso, and L-1 on G-tolerance do not appear to be related to a differential ability to maintain cardiac volumes. L-1 must provide more G protection due to the isometric contraction component of the maneuver and its ability to increase blood pressure.

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INTRODUCTION

The straining maneuver is the oldest means of increasing tolerance to +Gz acceleration (1,3). With the present G-induced loss of consciousness problem in tactical aircraft (4), completely understanding the effect of the straining maneuver on the cardiovascular system is essential.

One common mistake made in performing the straining maneuver is that a Valsalva maneuver (elevating intrathoracic pressure against a closed glottis without isometric contraction of the rest of the body) is performed instead of an L-1 maneuver (performing a brief Valsalva maneuver and a whole body isometric contraction) (4,20). An extended Valsalva maneuver has been shown to decrease G-tolerance below the relaxed G-tolerance level (21), while the L-1 maneuver has been shown to improve G-tolerance (16). One mechanism suggested to explain why the Valsalva maneuver does not increase G-tolerance is the high intrathoracic pressure generated during the maneuver. This elevated pressure diminishes venous return and cardiac output, resulting in a lowered arterial blood pressure (1).

Isometric muscle contraction also increases G-tolerance (13,21). This is particularly significant since the L-1 maneuver is a combination of the Valsalva maneuver and a whole body isometric contraction.

Two-dimensional echocardiography non-invasively visualizes the heart in real-time and can provide reliable single beat measurements of cardiac volumes (11,18,19). Recently in our laboratory, two-dimensional echocardiographs were recorded in relaxed subjects during +Gz acceleration (8).

The purpose of this study was to evaluate the effect of performing an L-1 maneuver, a Valsalva maneuver, and a whole body isometric contraction on cardiac volumes at 1G and during +Gz acceleraton. Two-dimensional echocardiography was used to measure cardiac volumes.

METHODS AND MATERIALS

Subjects -- Ten healthy men, ages ranging from 21 to 30 years (mean age 25 years), participated in the two phases of the experiment after giving informed consent. Eight subjects participated in the 1G phase and seven subjects participated in the centrifuge phase. Five subjects participated in both phases. For the centrifuge phase, all subjects were experienced centrifuge subjects. The subjects had previously been screened to assure that high quality apical four-chamber echocardiograms were obtainable. The echocardiograph transducer was fixed to the subject's chest by a vinyl resin mount. Dual three lead EKG cables were attached to the subject. One set was used for subject monitoring and one set was used to record the cardiac rhythm with the echocardiograph. The subjects did not wear G-suits.

Echocardiographic technique -- Four-chamber apical echocardiographs were recorded using a 2.5 or 3.5 MHz transducer and a real-time, two-dimensional phased array sector scanner (Hewlett Packard Model 77020A). A 90° sector scan was recorded at 30 frames per second. In the centrifuge phase of the study, video images were transmitted through the centrifuge slip rings and stored on 0.5 inch video tape for later playback and analysis. Echocardiograms were recorded with the subject sitting.

STUDY PROTOCOL

1G Phase -- Subjects performed the Valsalva and L-1 maneuvers and whole body isometric contractions for 15 seconds. The three straining maneuvers were presented in a randomized fashion. At least 5 minutes separated the performance of each maneuver. The subjects were seated in a chair with a 30° seatback angle and dimensions similar to the F-16 seat.

Centrifuge Phase -- Each subject was exposed to a 30 second +4Gz (0.5 G/sec onset rate) acceleration profile while performing a Valsalva maneuver, an L-1 maneuver, or a whole body isometric contraction. For uniformity between conditions, the subjects started performing the maneuver at the start of the acceleration epoch. The three straining maneuvers were presented in a randomized fashion. At least 5 minutes separated each acceleration exposure. If the subject developed peripheral light loss (defined below) during the acceleration epoch, the centrifuge automatically came to a full stop.

Centrifuge -- The experiment was conducted on the Dynamic Environment Simulator, a 3 axis, 19 foot radius, man-rated centrifuge located at the Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio. An F-16 seat (30° seatback angle from vertical) was placed tangentially to the centrifuge's arc of revolution.

Straining Maneuvers -- All subjects were carefully instructed on the performance of the Valsalva and L-1 maneuvers and whole body isometric contraction. For the 1G phase, the subjects performed a Valsalva maneuver by blowing into a pressure gauge and maintaining a positive pressure of 40 mmHg. For the centrifuge phase, the subjects bore down against a closed glottis. There was no muscle contraction except for the thoracic and abdominal muscles. For the L-1 maneuver, the subjects performed a Valsalva maneuver as described above for the appropriate phase and simultaneously performed a whole body isometric contraction. For the centrifuge phase, the subjects were asked to bear down against the closed glottis with a similar force for both the Valsalva and the L-1 maneuver. This was done to generate similar intrathoracic pressures for both maneuvers. A more complete description of the Valsalva and L-1 maneuvers can be found elsewhere (4). With the whole body isometric contraction, the subjects tensed all their muscles without exerting any force against an external object. The subjects maintained a completely open glottis throughout the maneuver.

For the 1G phase, the respiratory rate was 1 every 5 seconds. The subject was prompted when to breathe by an investigator. During the centrifuge phase, the subject breathed at a rate of approximately once every 3 to 5 seconds. They set their own rate. For both the Valsalva and L-1 maneuvers, the subjects quickly exhaled and inhaled.

Peripheral Light Loss -- A subject was said to have had peripheral light loss (PLL) when the boundary of his visual field subtended an angle less than 60°. In order to monitor this function, an arc of light emitting diodes (LED) was placed in front of the seated subject. The position of two pairs of flickering lights, equidistant from the center, could be controlled by a force control stick. The subject tracked the LED pairs so that the lights remained at the border of his visual fields.

Data Collection -- Echocardiograms were recorded continuously for two minutes prior, during and two minutes following each maneuver at 1G and each acceleration exposure. Measurements for the 1G study were made at baseline, at the beginning (0-1 seconds) and end of a maneuver (4-5 seconds), and immediately following the three maneuvers. Measurements for the centrifuge study were made at baseline, initially at 4G, every 10 seconds for the next 30 seconds, immediately after the G exposure, and 30 seconds following termination of the exposure. If the subject experienced PLL, then a measurement was made at that point, immediately following termination of the exposure, and 30 seconds later.

Data Analysis -- Heart rate was determined by measuring the R-R interval on the echocardiogram. The cardiac volumes were determined by the single plane ellipse method. The frame with the largest ventricular area (just as the mitral valve closed) was chosen to be the end-diastolic frame. The end-systolic frame was selected by finding the frame with the smallest left ventricular area. Stroke volume was determined by subtracting the end-systolic volume from the end-diastolic volume. Cardiac output was determined by calculating the product of the stroke volume and heart rate. All calculations and measurements were made using the software incorporated in the Hewlett Packard echocardiograph (11). Previous work in our laboratory has shown that these measurements are reproducible with a 0.05 coefficient of variation.

Statistical Analysis -- To determine the significance of differences, in percent change, between the maneuvers, analyses of variance (ANOVA's) were used with subject and maneuver as the factors. For the percent change from 1G to initial 4G, the 3 maneuvers were compared using all 7 subjects. The data from two subjects were not used for comparison after the initial 4G data because they experienced PLL in two runs. T-tests were used to determine whether the percent change for any maneuver was different from 0. These tests used only those subjects who had not yet experienced PLL.

RESULTS

1G Phase -- Table 1 and Figure 1 show the 1G hemodynamic data. The heart rate increased during all maneuvers and there were no significant changes in heart rate between the different maneuvers. The end-diastolic volume decreased during the Valsalva and L-1 maneuvers. The changes from baseline to the end of both maneuvers were statistically significant ($p<0.05$). For both the L-1 and Valsalva maneuvers, the changes in stroke volume paralleled the changes in end-diastolic volume. After release of the L-1 and Valsalva maneuvers, the cardiac output increased significantly ($p<0.05$). The L-1 and Valsalva maneuvers produced similiar changes in all parameters.

Centrifuge Phase -- When performing the Valsalva maneuver, three of the seven subjects experienced PLL. Two of seven subjects experienced PLL when performing the whole body isometric contraction, and no subjects experienced PLL when performing the L-1 maneuver. All subjects, who experienced PLL, did so in the first 10 seconds of the 4G epoch.

Table 2 and Figure 2 illustrate the centrifuge hemodynamic data. The heart rate increased significantly from baseline throughout the 4G epoch for all maneuvers ($p<0.05$). As the acceleration epoch ended and the maneuvers were released, the heart rate returned toward baseline. For all maneuvers, the end-diastolic volume decreased initially ($p<0.05$), changed little throughout the acceleration epoch and then returned towards baseline following termination of the acceleration epoch. The decrease in stroke volume from the 1G baseline to initial 4G was significant for all maneuvers ($p<0.05$). Stroke volume remained below baseline throughout the G plateau for all maneuvers. Cardiac output increased for all maneuvers during the 4G epoch. There were no significant differences between the maneuvers for any percent change.

DISCUSSION

The current study found that isometric straining, the L-1 and the Valsalva maneuvers at 1G and 4G produced similar changes in cardiac volumes.

The end-diastolic volume decreased similarly during isometric straining, the L-1 and Valsalva maneuvers at both 1G and 4G. Since left ventricular end-diastolic volume is an indicator of venous return, the venous return to the left heart during the three maneuvers must also be simiiiar. This finding also shows that the combination of the Valsalva maneuver and the isometric straining, in the L-1 maneuver, does not augment blood return more than either maneuver alone. In fact at 4Gz, both the L-1 and valsalva maneuvers appear to augment venous return when compared to a relaxed subject at the same Gz level. In a previous study, relaxed subjects, wearing an uninflated G-suit, were exposed to the same acceleration epoch used in this study. In that study, the end-diastolic volumes decreased by 37% when the subjects just attained 4G compared to an 18% decrease in this study (Jennings, unpublished observations).

The elevated intrathoracic pressure produced by the Valsalva maneuver inhibits blood return to the heart at 1G (10). In the classic Valsalva maneuver, a forced expiration is held against a closed glottis for periods of 15-30 seconds. During the initial portion of the maneuver (phase I), there is an increase in the systolic and mean arterial blood pressure. This increase in blood pressure is thought to be caused by the transmission of the intrathoracic pressure elevation to the peripheral arterial system. After this initial phase at 1G, the effect of diminished venous return predominates and lowers blood pressure (2,15). During +Gz acceleration, there might be a cumulative effect of diminishing venous return when performing a series of L-1 or Valsalva maneuvers over time. The data from the current study does not support this hypothesis. End-diastolic volume did not continue to diminish appreciably over the 4G 30 second interval. In this study, the subject breathed rapidly and deeply approximately every 3-5 seconds between the maneuvers. Rapid inhalation generates higher negative intrathoracic pressures than occur with ambient respiration (20). Left ventricular end-diastolic volume increases with both negative intrathoracic pressure (2) and deep inspiration (5). The chest, in a sense, acts as a suction pump drawing blood back to the heart and the properly performed maneuver helps preserve venous return to the left heart.

A prolonged Valsalva maneuver (15 seconds) can lower G-tolerance (21). This decrease in G-tolerance has been attributed to diminished venous return (1). Since the L-1 maneuver has a similar short-term effect on cardiac volumes as the Valsalva maneuver, a prolonged L-1 maneuver may also diminish venous return and lower G-tolerance. During a prolonged straining maneuver, whether or not isometric contraction is being performed, diminished venous return and lower G-tolerance may occur. The frequency of the straining maneuver affects its efficacy. The straining maneuver must be repeated every 3-5 seconds as emphasized elsewhere (4,22).

Though the whole body isometric contraction, when combined with the Valsalva maneuver, does not seem to have an additive effect on venous return, it should not be construed that it has no role in G-protection. The L-1 maneuver provides greater G-protection than the Valsalva maneuver as shown here and elsewhere (22). Since the only difference between the two maneuvers is that a whole-body isometric contraction is performed with the L-1 maneuver, the isometric contraction of the L-1 maneuver must provide some additional G-protection. Isometric contraction of a muscle produces a blood pressure elevation (16). This blood pressure elevation can be due to an increase in cardiac output or, if the cardiac output is limited for some reason, to an increase in the peripheral vascular resistance (6). The effect of isometric contraction on blood pressure probably contributes to the enhanced G-tolerance of the L-1 maneuver. Other investigators have noted that the eye level arterial blood pressure increases as several consecutive L-1 maneuvers are performed during +Gz acceleration (17). The blood pressure response to isometric contraction occurs by 15 seconds (14). This time course would coincide with the observations of increasing eye level blood pressure over time. This reasoning leads to a new avenue of research: altering the performance of isometric contraction to maximize the blood pressure elevation.

There may be other means not identified in this study by which the Valsalva maneuver adversely affects G-tolerance. If an individual hyperventilates prior to performing a Valsalva maneuver, blood pressure begins to decrease sooner than expected (shorter phase 1). This effect is attributed to an increased cerebral vascular resistance and peripheral blood flow, which diminishes cereb lood flow and predisposes an individual to loss of consciousness (7). he detrimental effect of antecedent hyperventilation can be further intensified when venous return is simultaneously impaired (standing from a squatting position) (7). These two factors are important in the acceleration environment. Under high G acceleration, subjects hyperventilate (12) and venous return is substantially reduced during +Gz acceleration (8). hese factors may also affect the L-1 maneuver since the L-1 and Valsalva maneuvers produce simillar changes in cardiac volumes. Another means by which the Valsalva maneuver may decrease G-tolerance could be the impedence of venous return when extremely high intrathoracic pressures are generated. Under these conditions, venous return could transiently approach zero.

Recently a suggestion has been made that monitoring superficial temporal artery blood flow at 1G can be used to train pilots to perform a proper L-1 maneuver (9). The 1G results from the current experiment indicate that both the Valsalva and L-1 maneuvers have similar effects on cardiac volumes, suggesting that the 1G doppler flows may also be similar. Indeed, we have found identical 1G temporal artery doppler flow tracings in subjects, who were performing a Valsalva maneuver (an improper straining maneuver) and an L-1 maneuver. Our data suggests that using doppler flow velocities to train pilots at 1G must be approached with caution. The subject should be visualized to insure that he is performing an isometric contraction and breathing properly.

There are minor differences between the isometric contraction, the Valsalva and the L-1 maneuvers' effect on left ventricular end-diastolic volumes during +Gz acceleration. The differing ability of the L-1 and Valsalva maneuvers to improve G-tolerance appears related to the isometric contraction component of the L-1 maneuver and its ability to increase blood pressure.

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TABLE 1

Cardiovascular Effects of Isometric Straining, the L-1 Maneuver, and the Valsalva Maneuver at 1G

	Base to Beginning			Base to End			Beginning to End			End to Post		
	L-1	Val	Iso	L-1	Val	Iso	L-1	Val	Iso	L-1	Val	Iso
Heart Rate	9	7	4	24*	4	18*	13*	-2	13*	23**	28**	16*
End-Diastolic Volume	-3	-4	-9	-17*	-14*	1	-13*	-10	11	6	-6	-3
Stroke Volume	0	-3	-11*	-17*	-8	4	-17**	-5	17**	8	-7	-3
Cardiac Output	9	4	-5	2	-4	26*	-5	-6	32**	32**	19*	15

* .01 $p \leq .05$ - changes compared to zero
** $p \leq .01$ - changes compared to zero

1. Values are the mean percent change between listed conditions.
2. Base = Pre-Maneuver Baseline
3. Beginning = Start of Maneuver
4. End = End of Maneuver
5. Post = Post-Maneuver Baseline
6. Val = Valsalva Maneuver
7. Iso = Isometric Contraction

TABLE 2

Cardiovascular Effects of Isometric Straining, the L-1 Maneuver, and the Valsalva Maneuver During +Gz Acceleration

	Base to Initial 4G			Inital 4G to 10 sec 4G			Initial 4G to 20 sec 4G			Initial 4G to 30 sec 4G			30 sec to Post		
	L-1	Val	Iso	L-1	Val	Iso	L-1	Val	Iso	L-1	Val	Iso	L-1	Val	Iso
Heart Rate	42**	49**	57**	25	9	15	39*	16	14	36*	20	21	-19*	-35*	-9
End-Diastolic Volume	-16*	-16*	-20*	-3	5	-8	-5	-7	-9	-17	-6	-11	14	12	18
Stroke Volume	-17*	-20*	-23*	6	14	-11	-6	1	-13	-16	0	-12	17	6	10
Cardiac Output	19	27	19	32	13	3	26	8	-1	12	12	6	-7	-32	1

* .01 $p \leq .05$
** $p \leq .01$

1. Values are the mean percent changes between listed conditions.
2. Seven subjects were used for the baseline to the initial 4G data. For all other comparisons, seven subjects were used for the L-1 data, four subjects for the Valsalva data, and five subjects for the isometric data.
3. Base = Pre-Acceleration Baseline
4. Post = Post-Acceleration Baseline
5. Val = Valsalva Maneuver
6. Iso = Isometric Contraction

FIGURE LEGENDS

Figure 1: The effect of the Valsalva maneuver, the L-1 maneuver and isometric straining on mean percent change of a) heart rate, b) end-diastolic volume, c) stroke volume, and d) cardiac output at 1G.

Figure 2: The effect of the Valsalva maneuver, the L-1 maneuver, and isometric straining on percent change of a) heart rate, b) end-diastolic volume, c) stroke volume, and d) cardiac output during the 4G epoch. Only the four subjects who completed the three conditions without PLL were used in these graphs.

Figure 1

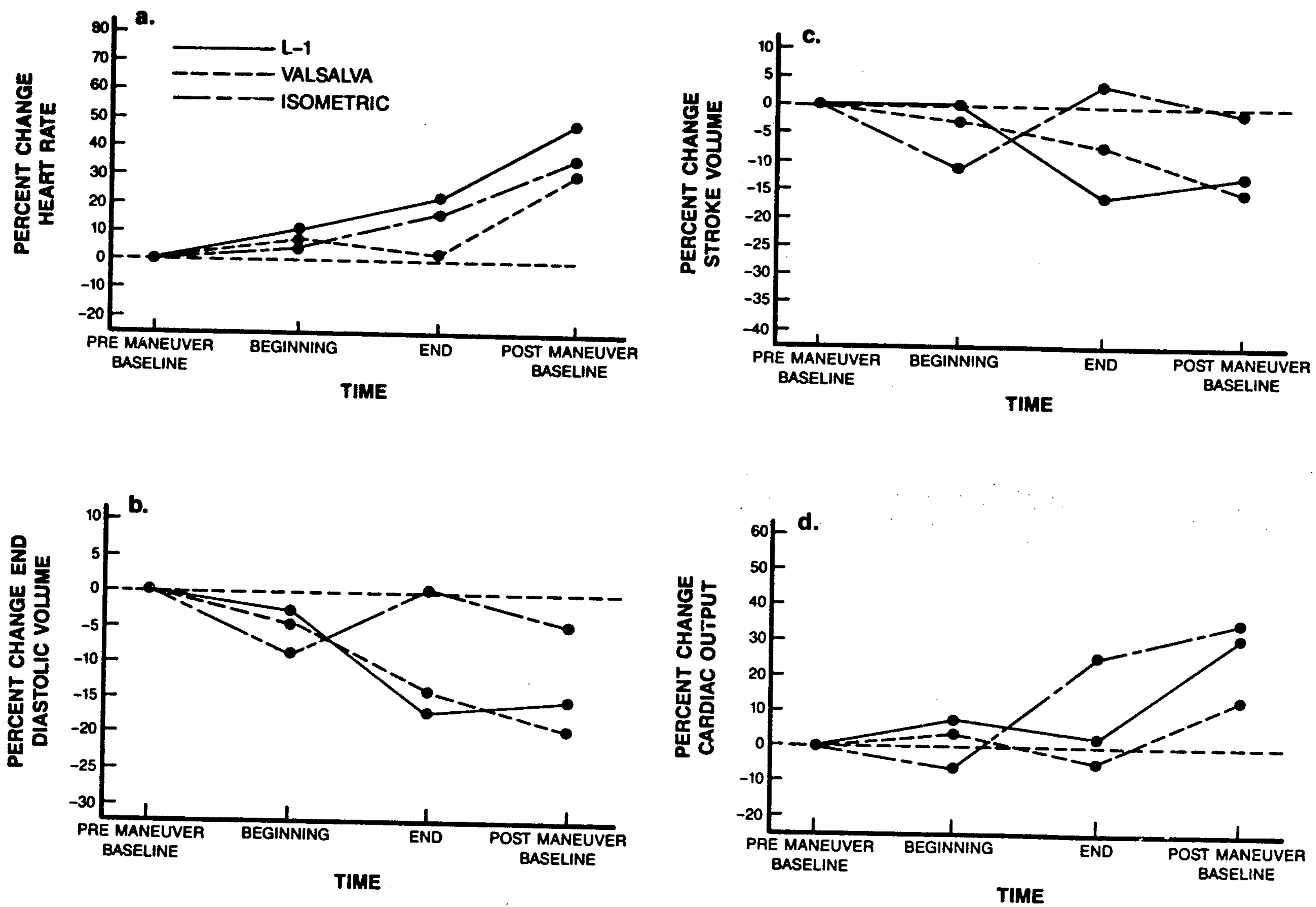
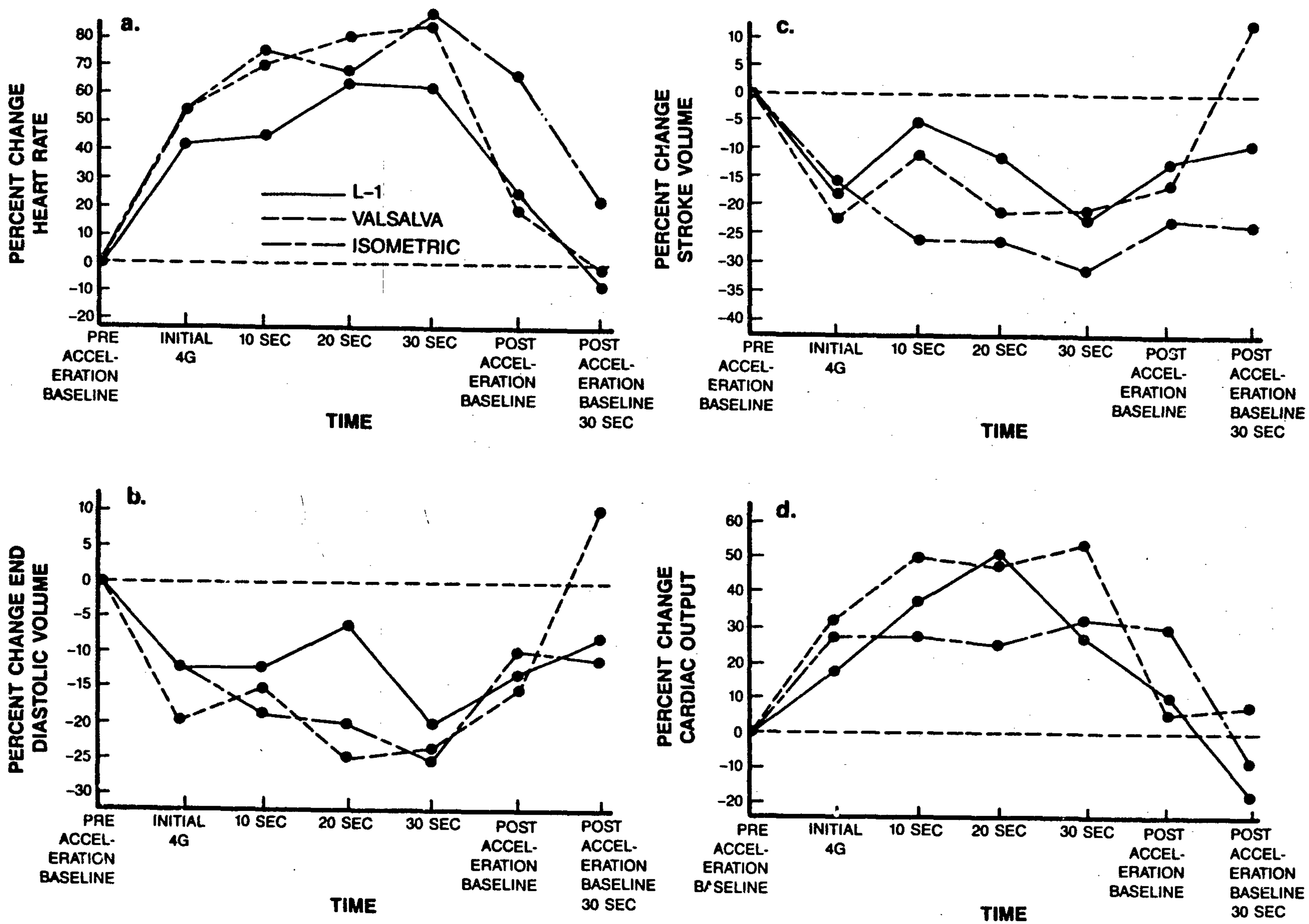

a.
PERCENT CHANGE HEART RATE
80
70
60
50
40
30
20
10
0
-10
-20
L-1
VALSALVA
ISOMETRIC
PRE MANEUVER BASELINE
BEGINNING
END
POST MANEUVER BASELINE
TIME
c.
PERCENT CHANGE STROKE VOLUME
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
PRE MANEUVER BASELINE
BEGINNING
END
POST MANEUVER BASELINE
TIME
b.
PERCENT CHANGE END DIASTOLIC VOLUME
10
5
0
-5
-10
-15
-20
-25
-30
PRE MANEUVER BASELINE
BEGINNING
END
POST MANEUVER BASELINE
TIME
d.
PERCENT CHANGE CARDIAC OUTPUT
60
50
40
30
20
10
0
-10
-20
PRE MANEUVER BASELINE
BEGINNING
END
POST MANEUVER BASELINE
TIME

Figure 2


a.
PERCENT CHANGE HEART RATE
80
70
60
50
40
30
20
10
0
-10
-20
L-1
VALSALVA
ISOMETRIC
PRE ACCEL-ERATION BASELINE
INITIAL 4G
10 SEC
20 SEC
30 SEC
POST ACCEL-ERATION BASELINE
POST ACCEL-ERATION BASELINE 30 SEC
TIME
c.
PERCENT CHANGE STROKE VOLUME
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
PRE ACCEL-ERATION BASELINE
INITIAL 4G
10 SEC
20 SEC
30 SEC
POST ACCEL-ERATION BASELINE
POST ACCEL-ERATION BASELINE 30 SEC
TIME
b.
PERCENT CHANGE END DIASTOLIC VOLUME
10
5
0
-5
-10
-15
-20
-25
-30
PRE ACCEL-ERATION BASELINE
INITIAL 4G
10 SEC
20 SEC
30 SEC
POST ACCEL-ERATION BASELINE
POST ACCEL-ERATION BASELINE 30 SEC
TIME
d.
PERCENT CHANGE CARDIAC OUTPUT
60
50
40
30
20
10
0
-10
-20
PRE ACCEL-ERATION BASELINE
INITIAL 4G
10 SEC
20 SEC
30 SEC
POST ACCEL-ERATION BASELINE
POST ACCEL-ERATION BASELINE 30 SEC
TIME